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Distribution of Energy in the Spectra of Platinum, Palladium, and Tantalum

A THESIS
SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

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University of Wisconsin
1911

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DISTRIBUTION OF ENERGY IN THE SPECTRA OF PLATINUM, PALLADIUM, AND TANTALUM

BY GEORGE VEST McCAULEY

In an early investigation of the emissive properties of certain solids Paschen[1] concluded that the spectral distribution of energy could be fairly well expressed by the empirical relation

$$E_{\lambda T}=C_1\lambda^{-a}e^{-\frac{C_2}{\lambda T}} \qquad (1)$$

for which the wave-length of maximum emission is given by the equation

$$\lambda_m T=\frac{C_2}{a}=\text{constant} \qquad (2)$$

where C_1, a, and C_2 are constants depending upon the substance, while T and λ denote absolute temperature of the source and wave-length respectively.

Subsequent attempts to verify this law for metallic radiators have led to widely different results. Lummer and Pringsheim,[2] working with platinum, but only for a very narrow range of temperatures, obtained results that seemed to confirm Paschen's conclusions except that they found the product, $\lambda_m T$, to be only 2620, which is somewhat less than the value obtained by Paschen. Lummer and Kurlbaum,[3] on the other hand, and more recently, W. W. Coblentz,[4] have shown that the exponent "a" is not constant for any one metal, but must be regarded as a function of the temperature if Paschen's law is to express metallic emission. A further result of Coblentz's[5] investigation was that the wave-length of maximum emission, when computed from a single isothermal energy-curve by means of the easily obtained relation,

$$\lambda_m=\frac{\lambda_1\lambda_2\log\frac{\lambda_2}{\lambda_1}}{(\lambda_2-\lambda_1)\log e}, \qquad (3)$$

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[1] *Weid. Annalen*, **58**, 455, 1896; **60**, 662, 1897.

[2] *Ber. d. Deutsch. phys. Ges.*, **1**, 215, 1899.

[3] *Ibid.*, **17**, 106, 1898.

[4] *Bul. Bur. Standards*, **5**, 339, 1909.

[5] *Phys. Rev.*, **29**, 553, 1909.

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previously used by Paschen,[1] was not constant, but increased with increased differences of λ_1 and λ_2. Since equation (3) demands only the general assumption that C_1, a, and C_2 be functions only of the temperature, this result seemed to indicate that even in this more general form Paschen's law was inadequate.

By assuming the empirical law,

$$E_{\lambda T}=C_1\lambda^{-a}\frac{1}{e^{\frac{C_2}{\lambda T}}-1} \tag{4}$$

which is similar to the energy distribution law deduced by Planck[2] for a "black body," and computing the wave-length of maximum emission for a given isothermal curve, Coblentz[3] obtained results that were more nearly constant than with Paschen's form of the law.

In order further to determine the relative agreement of the two assumed laws (1) and (4) with experimental data, the present investigation was undertaken. It was proposed also to compare the emission of the metals studied with that of a "black body," a comparison which had hitherto been impossible because of the lack of an accurate method for measuring the true temperatures of incandescent metal filaments.

In selecting a criterion with which to test the two laws (1) and (4), the writer wished to avoid any that demanded an accurate knowledge of the wave-length of maximum emission. This seemed desirable in view of the difficulty of locating the exact position of this maximum because of atmospheric absorption bands.

The desired end was attained by the following simple solution of equations (1) and (4):

Let E_1, E_2, and E_3 be the emissivities at a given temperature T for the wave-lengths λ_1, λ_2, and λ_3 such that

$$\lambda_3=2\lambda_1=4\lambda_2\,.$$

Then since C_1, a, and C_2 are assumed to be functions only of the temperature, equation (1) admits of the solution

$$a=\frac{2\log\frac{E_1}{E_3}+\log\frac{E_1}{E_2}}{\log 2} \tag{5}$$

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[1] *Wied. Annalen*, 60, 665, 1897.

[2] *Vorlesungen über die Theorie der Wärmestrahlung*, Leipzig, 1906.

[3] *Phys. Rev.*, 31, 317, 1910.

and similarly equation (4) admits of the solution

$$a=\frac{2\log\frac{E_1}{E_3}+\log\left\{\frac{E_1}{E_2}+\frac{2E_3}{E_1}+\sqrt{\left(\frac{E_1}{E_2}\right)^2-\left(\frac{2E_3}{E_1}\right)^2+\frac{4E_3}{E_2}}\right\}}{\log 2}-1 \tag{6}$$

which should be constant for a given isothermal curve, if the assumed laws are correct.

For comparing the emission of the metals with that of a "black body," the true temperatures of the metal filaments were first measured and the "black-body" emission for all wave-lengths and this same temperature computed by means of Planck's "black-body" distribution law,

$$E_{\lambda T}=C_1\lambda^{-5}\frac{1}{e^{\frac{C_2}{\lambda T}}-1}\,. \tag{7}$$

Then by assuming Kirchhoff's law

$$\frac{E_{\lambda T}}{\epsilon_{\lambda T}}=A_{\lambda T}=(1-R_{\lambda T}) \tag{8}$$

where $E_{\lambda T}$, $A_{\lambda T}$, and $R_{\lambda T}$ represent the emissive, absorptive, and reflecting powers respectively of the metal, while $\epsilon_{\lambda T}$ denotes the corresponding emissivity of a "black body," the reflecting powers of the metals were determined as a function of wave-length and absolute temperature.

METHOD AND APPARATUS

The energy-curves were obtained with the usual spectro-bolometric arrangement shown in Fig. 1. The radiating source at O was inclosed in a suitable vacuum chamber V_1 separated by a rock-salt window W_4 from the large vacuum chamber V_2 which inclosed the entire spectrometer and bolometer. Thus the whole path of the radiant energy was *in vacuo* to eliminate atmospheric absorption as far as possible. The pressure in the spectrometer inclosure was maintained at about 15 mm of mercury by means of a water aspirator.

The spectrometer was of the Wadsworth[1] prism-mirror fixed arm type, furnished for part of the work with a rock-salt prism of

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[1] *Phil. Mag.*, **38**, 337, 1894.

$59°57'44''$ refracting angle, 7-cm refracting edge, and 11-cm base, for the rest with a rock-salt prism of $60°5'35''$ refracting angle, 8-cm refracting edge, and 6-cm base.

The slit-width was such as to give an image at the bolometer strip of the same width as the strip itself and was maintained constant for all parts of the spectrum to insure the best possible agreement of measured and actual energy as pointed out by Runge.[1]

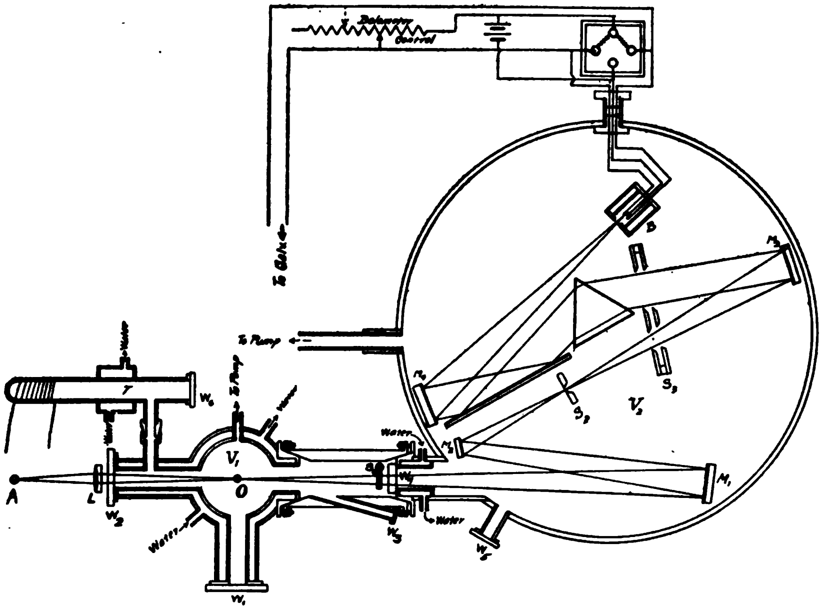

FIG. 1

The galvanometer used was described in a previous paper by Weniger.[2] It had a total resistance of about 7 ohms, a period of approximately 6 sec. with which it was practically aperiodic, and a current sensibility of 4×10^{-10} amperes for a deflection of 1 mm at a distance of 1.5 m. Suitable resistances were placed in series with the galvanometer to reduce its sensibility for work in the various parts of the spectrum.

Two bolometers were employed with strips 12 mm long, blackened with camphor smoke. With the large prism the bolometer width was 0.2 mm and with the small prism 0.5 mm. The remaining arms of the bolometer bridge were made of No. 22 manganin wire to minimize thermal effects. These coils were wound non-inductively, in the usual way, on a water-filled brass cylinder of about 300 cc capacity and were inclosed in a small wooden box outside the spectrometer vacuum for convenience of adjustment. The bridge balance was controlled by shunting the proper coil with a high resistance, a method recently employed by Abbot and now in general use in this laboratory.

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[1] *Zeit. f. Math. und Phys.*, **42**, 205–213, 1897.

[2] *Phys. Rev.*, **31**, 393, 1910.

The vacuum chamber V_1 (Fig. 1), in which the filaments were operated, consisted of a water-cooled brass tank of 12.5 cm internal diameter and 20 cm high supported from the large tank V_2 by means of a brass sleeve. The base, to which was attached all the electrical connections and mountings for the filaments, was also water-cooled and detachable. The tank and connecting sleeve were provided with windows W_1, W_2, and W_3 for purposes of calibration and temperature measurements. A steel tube, T, with a water-cooled jacket was fitted to the tank and used for heating calcium[1] to absorb residual oxygen and nitrogen. A triple metal screen S_1 was placed just in front of the rock-salt window W_4 and operated as a shutter through a packed joint in the lower side of the sleeve. All joints were conical and ground to fit, so that a thin film of tallow and beeswax mixture rendered them absolutely tight.

The metal filaments were mounted on heavy copper posts and were capable of being displaced laterally to a slight extent by rotating the base of the tank. This provided for focusing the filaments on the slit and for rotating them to one side during the galvanometer-bolometer calibration to be described later. The copper post clamping the lower end of the filament passed through a packed joint and was provided with an adjusting screw by means of which the filaments could be kept straight at all temperatures.

THE ENERGY-CURVES

The galvanometer deflections were read for successive angles of incidence differing by one minute of arc for a considerable distance on each side of and through the region of maximum emission.

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[1] Soddy, *Proc. Roy. Soc.*, 78, 439, 1906.

For the extreme short and long wave-length portions of the spectrum, the angle of incidence was varied by five minutes of arc. The sensibility of the galvanometer was adjusted, whenever possible, so that the deflections, which were observed to the nearest millimeter, were 10 cm or more. The zero reading was taken before and after each deflection to correct for drift which was small and uniformly steady in one direction during the time necessary to obtain several energy-curves.

The galvanometer deflections were found to be not proportional to the energy falling upon the bolometer strip, which necessitated a proportionality correction determined as follows:

A wide filament carbon lamp, furnished by the General Electric Co., was placed at *A* (Fig. 1) behind the source *O*. An achromatic combination of lenses *L* formed an image of the carbon filament at *O*, the metal filament being rotated now to one side. The prism was then turned 44′ from the minimum deviation position of the D-line, corresponding to a wave-length of $1.6\,\mu$ or $1.7\,\mu$ depending upon the prism used, and the temperature of the carbon filament raised to 1457°C. "black-body" temperature as measured with an optical pyrometer using wave-length $0.658\,\mu$. By means of rotating sectors the radiation from the carbon filament was reduced in intensity in known ratios, and the corresponding deflections of the galvanometer observed. The unit of intensity was arbitrarily chosen as one-twentieth of the intensity of the carbon lamp radiation with no sector interposed. In this way a calibration-curve was obtained connecting galvanometer deflections with units of intensity by means of which it was possible to transform at once from deflection-displacement to intensity-displacement curves.

This calibration was made each time that a series of observations was taken and was made for each sensibility of the galvanometer. Energy-curves thus obtained at widely different times could be compared readily and were not affected by sensibility changes of the bolometer or galvanometer for any given arrangement of the spectrometer.

When using the narrower bolometer strips and corresponding slit-width it was found unnecessary to apply the slit-width correction of Runge (*loc. cit*), the first term of which made less than 1 per cent change in the intensity in the region of maximum emission where the correction is greatest. With the wider bolometer strips, however, it was necessary to use the first term of the correction.

The dispersion correction for converting prismatic to normal energy-curves was obtained in the usual manner from the dispersion-curve of rock-salt and the computed spectrometer readings for the minimum deviation corresponding to various refractive indices.

The dispersion-curve used in the calibration was obtained from the data[1] of Martin's, Rubens, Rubens and Snow, Langley and Abbot,[2] and was corrected for *vacuo* by means of the dispersion-curve of air determined by Kayser and Runge,[3] extrapolating to long wave-lengths by means of the dispersion formula

$$n=1.000288\,17+1.316\,\lambda^{-2}+31600\,\lambda^{-4}$$

which these investigators found would express their results as far as the dispersion had been determined.

The above extrapolation was deemed justifiable in view of the fact that it gave correct wave-lengths for the experimentally located positions of the atmospheric absorption bands at $1.1\,\mu$, $1.4\,\mu$, $1.8\,\mu$, and $2.6\,\mu$ in the solar spectrum and for the CO_2 emission band at $4.4\,\mu$ of the bunsen burner.

The mean wave-length of the D-lines was chosen as the zero of reference; and the emission band at $4.4\,\mu$ from the bunsen burner, together with the sylvite absorption bands at $3.2\,\mu$ and $7.2\,\mu$, were used as checks on the accuracy of the spectrometer adjustments. The zero setting and check were always made first in air, using for this purpose the dispersion-curve of rock-salt with respect to air. Then after evacuating the spectrometer tank, the bunsen burner emission was observed again to check the vacuum correction applied to the dispersion-curve. In each case the band at $4.4\,\mu$ was located to within less than 0.5 per cent of the computed position.

THE "BLACK-BODY" ENERGY-CURVES

The "black-body" emission with which the metallic emission was compared was not measured directly, but was computed by means of Planck's distribution law in the following manner.

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[1] Kayser, *Handbuch der Spectroscopie*, 4, 493.

[2] *Annals of Astrophys. Obs.*, 1.

[3] *Astron. and Astrophys.*, 428, 1893.

With an arbitrary value of the constant C_1 in the above law, the "black-body" emission was computed for the absolute "black-body" temperature T_b at which the filament was operated and for the particular wave-length, 0.658 μ, at which the "black-body" temperature was measured. Equating this computed "black-body" emission to the observed metallic emission for this same wave-length, by virtue of the definition of "black-body" temperature, a value of C_1 was obtained which would refer the computed "black-body" emission to the same unit as the observed metallic emission. With this new value of the constant C_1 a "black-body" energy-curve was then computed for the absolute true temperature T_t of the metal filament. The inverse ratio of the ordinates of this curve to those of the observed energy-curve determined the reflecting powers according to equation (8).

TEMPERATURE MEASUREMENTS

The metals were obtained in sheet form ranging from 0.1 to 0.2 mm thick. After rolling to about 0.05 mm they were cut into strips 3.5 cm long by 7 mm wide and folded into wedge-shaped filaments with 12° openings. The true temperatures were measured through the window W_1 (Fig. 1) in the manner described by Professor Mendenhall[1] with an optical pyrometer of the Holborn-Kurlbaum type[2] calibrated from the palladium point as measured by Day and Sosman.[3]

In the case of tantalum the "black-body" temperatures were measured simultaneously with the "true" temperatures through the window W_3 by Dr. Forsythe and the writer as explained in the paper[4] referred to above. The relation of "true" to "black-body" temperature for this metal is shown in curve *a* (Fig. 2). In the case of platinum and palladium this relation was obtained from data by Professor Mendenhall,[5] and Waidner and Burgess[6] respectively and is shown in curve *b* (Fig. 2).

[1] *Astrophysical Journal*, **33**, 91, 1911.

[2] C. E. Mendenhall, *Phys. Rev.*, **33**, 74, 1911.

[3] *Amer. Jour. Sci.* (4), **29**, 93, 1910.

[4] *Astrophysical Journal*, **33**, 91, 1911.

[5] *Loc. cit.*

[6] *Bul. Bur. Standards*, **3**, 202, 1907.

EXPERIMENTAL RESULTS

Tantalum.—This metal was obtained from Siemens & Halske, and after rolling was polished with No. 0000 emery paper and washed free from grease and moisture with alcohol. The vacuum in which it was operated was maintained for two days with a Pfeifer rotating mercury pump running continuously, and the calcium was kept at a cherry-red heat for five or six hours prior to making observations. These precautions were found necessary because of the great influence of residual gases and grease on this metal at temperatures above 700° C. In the preliminary work it was found that the slightest trace of residual gas would cause the resistance to increase rapidly, and the metal would become brittle, losing its smooth metallic surface. This was also observed by Coblentz[1] and Pirani.[2] With continuous pumping from a per-

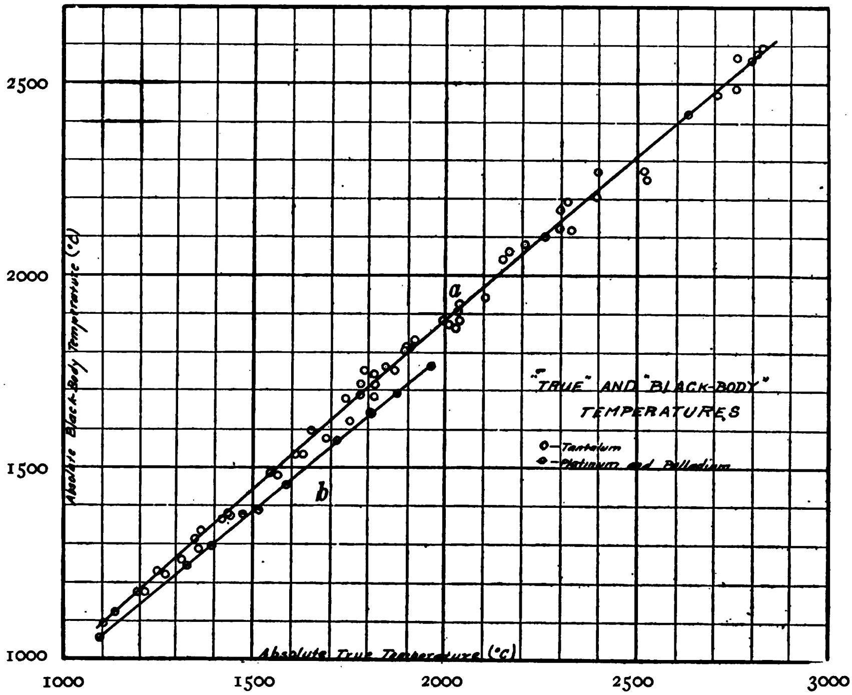

FIG. 2

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[1] *Bul. Bur. Standards*, **5**, 374, 1909. [2] *Ber. d. Deutsch. phys. Ges.*, **5**, 308, 1910.

fectly tight vacuum tank and with heated calcium, it was possible to operate the filaments throughout the entire range of temperatures to within a few degrees of the melting-point of the metal. Even at the very highest temperatures the current and voltage would remain constant, which was considered good working-conditions. After making the observations for five or six isothermal curves, the filaments were found to be ductile with a bright metallic surface as initially, except that they showed the effects of flaking produced by the high temperatures.

The values of "a" computed from equations (5) and (6) were not constant but diminished rapidly at first, reaching an approximately constant value at long wave-lengths. The departure from constancy was more marked in the case of the first of the assumed laws. It must be concluded, therefore, that previous measurements of the temperature variation of this exponent, based upon the assumption that a law of form (1) completely expressed the observed facts, are open to adverse criticism. No consistent variation of "a" with temperature was observed in this instance for a given region of the spectrum. The variation observed with increasing wave-length means nothing more than an erroneous initial assumption regarding the law of energy distribution. Had the assumption demanded the "constants" of (1) and (4) to be functions of wave-length, quite other conditions than (5) and (6) would have resulted for testing the respective laws.

The reflecting powers of tantalum as computed in the manner previously described from a comparison with "black-body" emission are shown in Fig. 3. Curve a, shows the values obtained by Coblentz[1] from direct reflection experiments made at room temperature. It is to be observed that the reflecting power diminishes with increasing temperature for wave-lengths greater than $0.7\,\mu$, the decrease being most rapid in the region from $0.8\,\mu$ to $2.0\,\mu$, wherein occurs a minimum reflecting power for high temperatures. For wave-lengths less than $0.7\,\mu$ there seems to be an increase of reflecting power with temperature. This increase was also observed from measurements of the "true" and "black-body" temperature at 0.658 μ with optical pyrometers.[1] The reflecting powers obtained by this method are shown in Fig. 4, curve *a*.

---

[1] *Bul. Bur. Standards*, 7, 207, 1911.

The variations of the product $\lambda_m T$ with temperature are indicated by Fig. 5. The wave-lengths λ_m were not computed by means of any formula resulting from an assumed energy distribution, but were taken directly from the experimental curves. The relation

$$\lambda_m T = \text{const.}$$

is seen at once not to obtain for tantalum. The wave-length of maximum emission shifts much more slowly toward shorter wave-

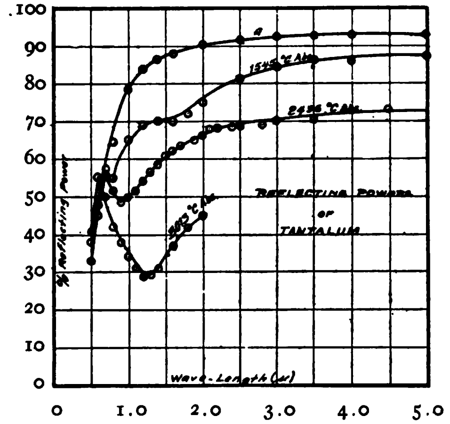

FIG. 3

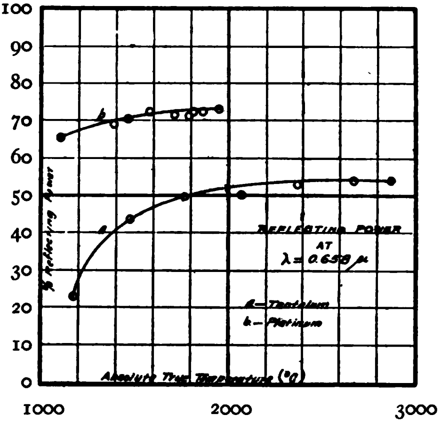

FIG. 4

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[1] Let E and E' be the emissivities of the metal from within the wedge and from the outside surface respectively as measured with the pyrometer. Let T_t and T_b be the corresponding "true" and "black-body" temperatures. Then by definition of these temperatures we have by Wien's "black-body" distribution law

$$\frac{E'}{E} = \frac{C_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T_b}}}{C_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T_t}}} = e^{\frac{C_2}{\lambda}\left(\frac{1}{T_t} - \frac{1}{T_b}\right)}$$

or

$$\log \frac{E'}{E} = \frac{C_2}{\lambda}\left(\frac{1}{T_t} - \frac{1}{T_b}\right) \log e$$

Then by assuming Kirchhoff's law

$$\log \frac{E'}{E} = \log a = \log (1 - R) = \frac{C_2}{\lambda}\left(\frac{1}{T_t} - \frac{1}{T_b}\right) \log e$$

from which the reflecting power (R) may be computed as soon as T_t and T_b are known.

lengths with increasing temperature than for a "black body," especially at the higher temperatures. Furthermore, tantalum has its maximum emissivity for low temperatures at a shorter wave-length, and for high temperatures at a longer wave-length than does a "black body."

A few of the spectral energy-curves for tantalum are shown in Fig. 6. They are seen to be perfectly continuous with no bands of selective emission. In general form the curves do not differ strikingly from "black-body" energy-curves, of which one is shown in curve *a* (Fig. 6) to the same scale. The emissivity of tantalum, however, diminishes more rapidly than that of the "black body" at the same temperature in the infra-red.

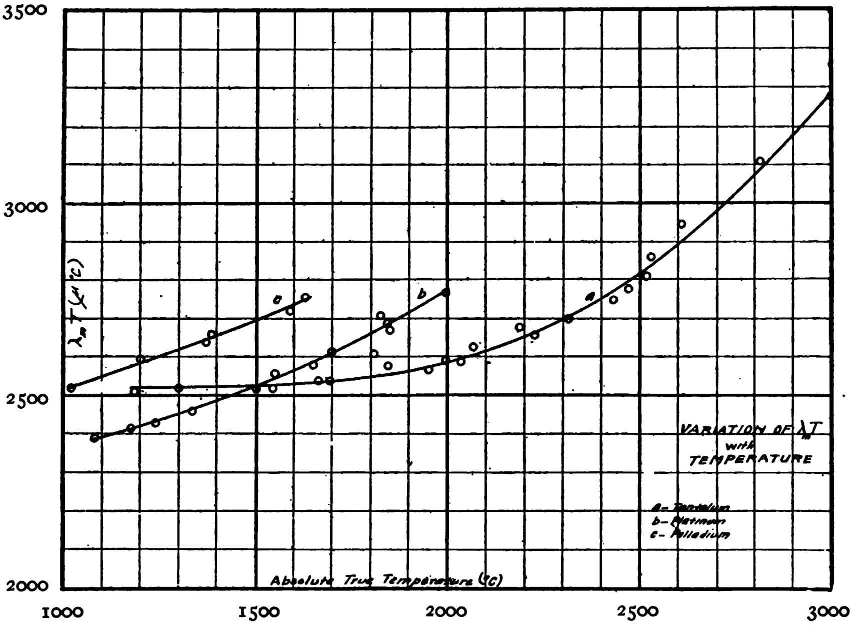

FIG. 5

Platinum.—The filaments for this part of the work were cut from platinum obtained from the firm of Baker & Co. They were polished, first with a rounded steel tool on a smooth plate glass, then with No. 0000 emery paper, and cleaned with a dry cloth. They were operated under a pressure of less than 0.1 mm of mercury, merely to eliminate atmospheric absorption as far as possible.

The values of "*a*" computed as for tantalum showed similar variations indicating a better agreement in the case of the second of the assumed laws. Here, also, no consistent variation of this exponent with temperature was observed.

A comparison of the spectral energy-curves with those of a "black body" gave the reflecting powers shown in Fig. 7. Curve *a* was obtained from values observed by Coblentz[1] at room temperature. The same general variations occur here as for tantalum except that the reflecting power in the visible spectrum is more nearly constant for platinum. This constant value in the visible is better illustrated in curve *b* (Fig. 4) which gives the reflecting powers computed from the relation between "true" and "black-body" temperatures at 0.658 μ as determined by Professor Mendenhall.[2]

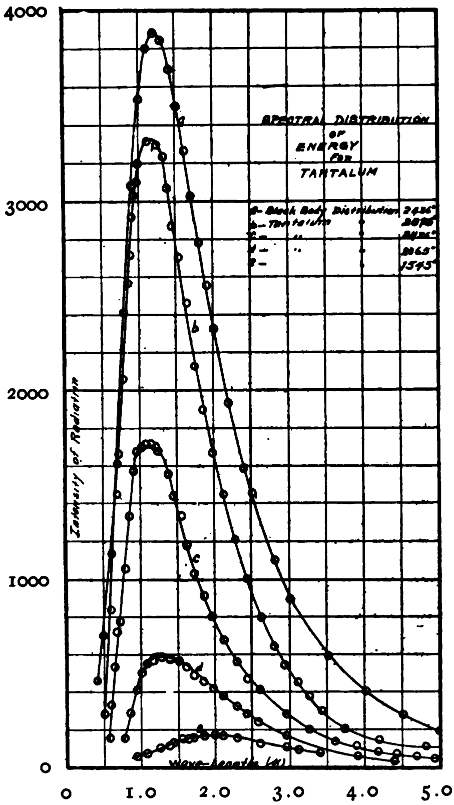

FIG. 6

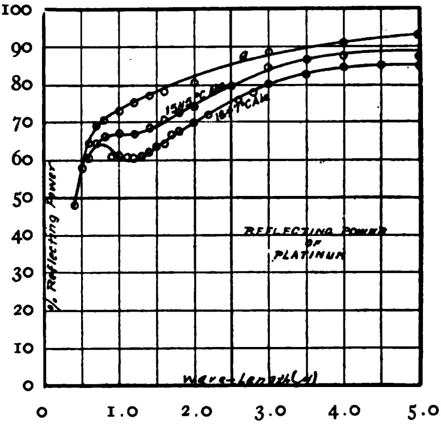

FIG. 7

The variations of $\lambda_m T$ with temperature are shown in Fig. 5. It will be seen that the same general tendency for this product to increase with temperature obtains here as for tantalum, the increase being more rapid at the higher temperatures.

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[1] *Bul. Bur. Standards*, 7, 207, 1911.

[2] *Astrophysical Journal*, 33, 91, 1911.

The spectral distribution-curves are shown in Fig. 8. They are seen to be very similar to those of tantalum, showing a rapid decrease of emission in the infra-red as compared with "black-body" emission shown in curve *a*.

Palladium.—This metal was obtained from Eimer & Amend, and after being rolled to the required thickness was polished with No. 0000 emery paper. The filaments were operated under the same conditions as the platinum. Some difficulty was experienced in keeping the wedge from opening at the higher temperatures, but by repeated trials it was possible to obtain energy-curves for temperatures ranging from 1000° to 1600° abs.

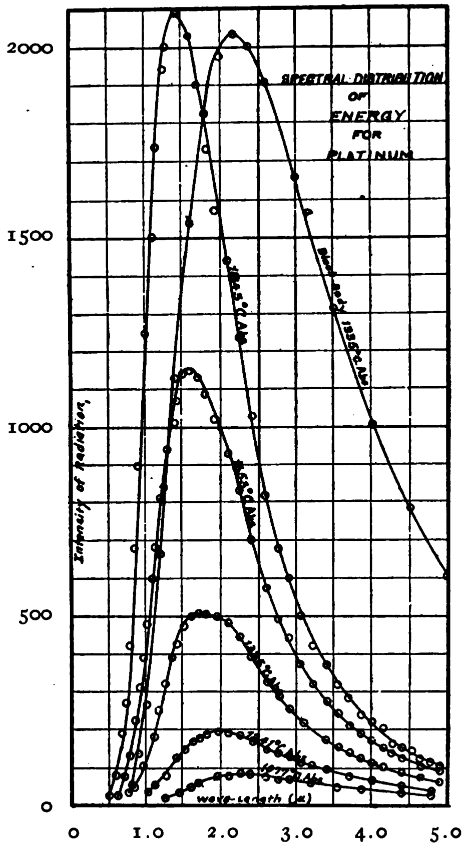

FIG. 8

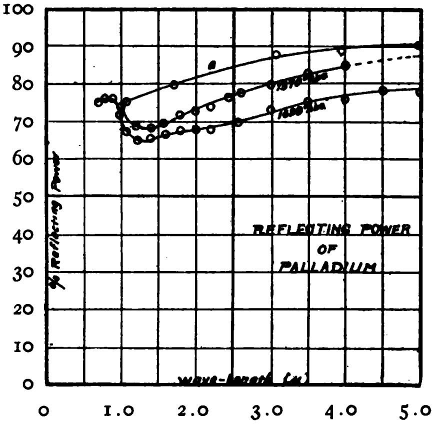

FIG. 9

Owing to the small amount of energy available in the long and short wave-lengths for temperatures at which this metal was operated, it was possible to obtain values of "*a*" through only a narrow region of the spectrum. Even in these narrow limits, however, the evidence seemed to be in favor of the second of the assumed laws.

The reflecting powers computed as for tantalum and platinum are shown in Fig. 9. Curve *a* gives the values observed by Coblentz.[1]

The dependence of $\lambda_m T$ upon temperature is seen from Fig. 5 and is similar to that of platinum. The values are higher for a given temperature than for either of the other metals, indicating that there is no direct relation between atomic weight and wave-lengths of maximum emission as suggested by Kayser,[2] from the early work of Jacques.

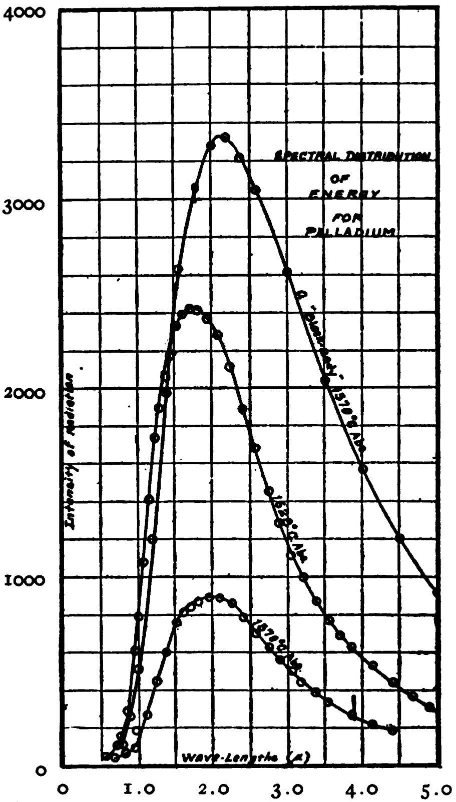

FIG. 10

In Fig. 10 is shown the energy distribution for two temperatures together with that of a "black body."

Owing to the fact that these curves as well as those for platinum were obtained at a time when the humidity of the atmosphere was high, a slight fogging of the rock-salt window separating the two vacuum chambers was practically unavoidable when the smaller chamber was opened to replace the filaments. Consequently the water vapor absorption band at 1.8 μ shows much stronger in these curves than in the tantalum curves, making the wave-length of maximum emission for some of the curves less certain.

DISCUSSION OF RESULTS

The constant decrease in the values of "*a*" as the longer wave-lengths are considered proves without a doubt the inadequacy of the assumed laws (1) and (4). Even for the second of these, which shows the better agreement, the departure from observed values is considerable. Assuming a constant mean value of "a" as determined for a given isothermal curve, the computed emission is in general from four to seven times smaller than the observed values at 6.0μ. The agreement is, of course, better for shorter wave-lengths, but correspondingly worse for longer ones.

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[1] *Bul. Bur. Standards*, **2**, 470, 1906.

[2] *Handbuch der Spectroscopie*, **2**, 92.

Reflecting powers determined in the manner here described are apt to be in error by several per cent, as the "black-body" curves were obtained from a knowledge of the emissivity of the metals at a part of the spectrum where bolometric measurements are somewhat uncertain. The error in the present instance arising from this source was estimated to be from 2 to 10 per cent, being less, of course, at high temperatures. Absolute values only are affected in this way, hence the reflecting powers obtained in this manner show in a qualitative way the relative emissivities of a metal for various wave-lengths and temperatures.

The diminution of reflecting power with increasing temperature for long wave-lengths is in qualitative agreement with the measurements of Hagen and Rubens[1] on the reflecting power of platinum for the residual rays of fluorite as a function of temperature.

The shift of wave-length of maximum emission (Fig. 5) is less rapid for tantalum than for platinum or palladium for low temperatures. Hence temperature estimates[2] of tantalum made from the relation

$$\lambda_m T = 2620,$$

which Lummer and Pringsheim[3] found for platinum, is correct only for a temperature in the neighborhood of 2000° abs.

Fig. 11 shows the agreement of the values of $\lambda_m T$ for platinum with those observed by Paschen.[4] The values obtained by the previous investigator are lower in general than those of the present writer, which, however, are more consistent among themselves. The slight disagreement may be due to the different temperature scales employed or to conduction losses from the thermocouples used in the earlier work for measuring temperatures. The constant value found by Lummer and Pringsheim seems to have been in error, due possibly to the small temperature range employed, or to lack of polish of the radiating surface. This latter would tend to give a constant value of $\lambda_m T$ as indicated by Pachen's[1] results for such poorly reflecting substances as iron oxide, copper oxide, and lampblack.

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[1] *Ann. d. Phys.*, 11, 888, 1903.

[2] W. W. Coblentz, *Bul. Bur. Standards*, **5**, 375, 1909.

[3] *Loc. cit.*

[4] *Ann. d. Phys.*, **60**, 70, 1897.

SOURCES OF ERROR

The usual errors attendant upon spectro-bolometric measurements from scale readings and subsequent reduction to energy were manifest here. These were minimized as far as possible by employing large deflections, and were estimated to be less than 1 per cent except for the long and short wave-length extremities of the curves. The use of a rock-salt prism further reduced the possibility of error in making the dispersion correction in the region of maximum emission. The point of inflection of the dispersion-curve, at which the dispersion correction is difficult to determine, occurs at about 3.0 μ for rock-salt and hence is well beyond the wave-length of maximum emission except for very low temperatures.

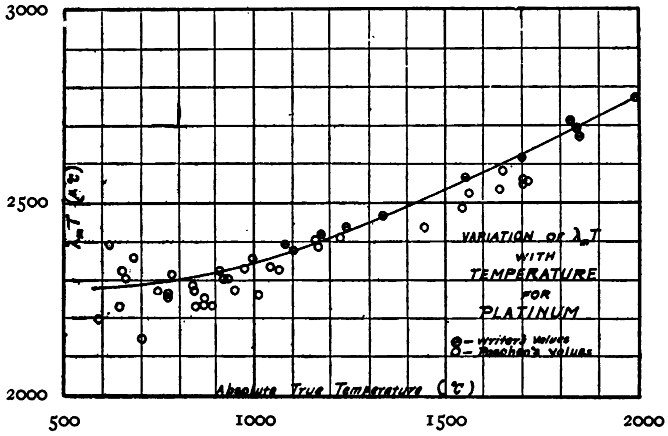

FIG. 11

Of the constant errors, the reduction of the rock-salt dispersion to *vacuo* is perhaps the most questionable. The CO_2 emission check previously described, however, seemed to justify such a correction. That there are no regions of anomalous dispersion for air as far as 20.0 μ is known from determinations of the dispersion of rock-salt, fluorite, sylvite, quartz, and other substances with respect to air for this region of the spectrum. It is possible that the dispersion-curve of air may have a point of inflection in the infra-red, similar to that of rock-salt and fluorite. This would tend to diminish the corrected values of the refractive indices in the dispersion-curve of rock-salt and would thereby increase the corrected wave-lengths in the infra-red. If such a point of inflection does occur in the dispersion-curve for air, it must be beyond 4.4 μ or else the departure from the assumed law is small, as the precise location of the CO_2 emission band indicates.

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[1] *Ann d. Phys.*, **58**, 455, 1896; **60**, 663, 1897.

To make sure that no constant error was being introduced by using the bunsen burner emission as a check for the vacuum correction to dispersion and for the zero displacement, it was necessary to show that the position of this band was not altered by the absence of CO_2 in the path of the ray. This was accomplished by observing its position in air containing CO_2 and then in air freed from this gas. Its position was found to be unaltered by the absence of CO_2.

Zero changes of the spectrometer, which are usually very troublesome and almost inevitable, were reduced to a minimum in this instance by the use of iron fittings and mirror supports for the spectrometer. Every part of the spectro-bolometer was carried by heavy iron rods and castings from the base of the spectrometer.

A final source of error is that due to the possible non-black character of the bolometer for certain regions of the spectrum. Any error from this source, however, as shown by Royds,[1] would be of the order of 1 per cent or less beyond 0.8 μ and is therefore negligible in this instance.

SUMMARY

The results of the present investigation may be summarized as follows:

1. The distribution of energy in the spectra of tantalum, platinum, and palladium was determined for temperatures ranging from 1000° abs. to the respective melting-points of the metals.

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[1] *Phil. Mag.*, **21**, 172, 1911.

2. The assumed metallic radiation laws

$$E_{\lambda T}=C_1\lambda^{-\alpha}e^{-\frac{C_2}{\lambda T}}$$

and

$$E_{\lambda T}=C_1\lambda^{-\alpha}\frac{1}{e^{\frac{C_2}{\lambda T}}-1}$$

were tested by a simple method and were shown to be inadequate to express the emission of the metals.

3. The metals studied were shown to acquire a minimum reflecting power in the early infra-red, becoming more marked at high temperatures.

4. The dependence of reflecting power upon absolute temperature was shown to be similar for all three metals in the infra-red. In the visible spectrum, however, this dependence was found to be different for the different metals.

5. The product $\lambda_m T$ was found to be not constant, but increased rapidly with temperature. For tantalum the absolute value of this product was found to be greater than for a "black body" above 2600° abs.

6. No direct relation was found to exist between atomic weight and wave-length of maximum emission.

In conclusion the writer wishes to express his thanks to Professor Mendenhall for the many helpful suggestions offered and for the special apparatus necessary to carry on the investigation; also to Dr. W. E. Forsythe for his assistance in parts of the work.

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